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SUMMARY

A brief fixed-base simulator study was made of a pilot-controlled Gemini-Agena docking in which a fully illuminated Agena target was oscillated sinusoidally in three angular degrees of freedom about its midlength point. Docking flights were initiated at a range of about 300 feet and were made with only out-of-the-window visual observation of the target for guidance information. Both the rate-command (primary) and direct (back-up) modes were employed by the pilots for spacecraft attitude control. The results of the rate-command and direct-mode docking flights with the Agena target oscillating at $\pm 5^{\circ}$ amplitude in each of three angular degrees of freedom were comparable with those obtained with a rigidly stabilized target when the periods of the target oscillations were 160 seconds or greater. Below 160 seconds, increasing difficulty in task performance with corresponding less favorable pilot ratings were obtained as the period of the oscillations were reduced. Limited results on the effect of oscillation amplitude indicate that for an amplitude of $\pm 2.5^{\circ}$, target oscillations have little influence on the docking task except at the shorter oscillation periods (less than 30 seconds). For the amplitude range between $\pm 2.5^{\circ}$ and $\pm 10.0^{\circ}$, increasing motion amplitude for a given value of period (below 120 seconds) results, in general, in increases in fuel used, increases in flight time required, and less favorable pilot ratings. The effects on the docking task of different paths traced by the docking ring due to different yaw and pitch sine-wave combinations and the use of a sinusoidal wave form for target limit cycling were found to be of little consequence for most of the range of the oscillation periods.

INTRODUCTION

A major mission objective of the manned space flights in Project Gemini is the accomplishment of the rendezvous and docking of the Gemini spacecraft with an Agena target vehicle orbiting at an altitude of about 150 nautical miles. As a prerequisite to the actual space flight, a number of simulator studies (refs. 1 to 5, among others) have been made to examine various aspects of the docking such as the effects of spacecraft attitude control mode, control jet malfunctions, target illumination, and so forth. For these studies the Agena target was rigidly stabilized in attitude. This assumption is compatible with the operation of the attitude-stabilization system of the actual Agena vehicle which in the docking phase restricts target angular movements to very small amplitudes that are insignificant to the docking task. For that part of the space flight preceding the docking, however, the Agena attitude-stabilization system operates in the orbit phase where maximum angular amplitudes larger by a factor of 10 or more than those of the docking phase are permitted in order to conserve attitude fuel. The present investigation was undertaken to examine, briefly, the possibilities of docking during this latter phase of target stabilization and to define target oscillatory conditions for which significant degradations in the pilot's task performance would occur. Docking flights were made in which the target was oscillated sinusoidally in three angular degrees of freedom (yaw, pitch, and roll) at a maximum amplitude of $\pm 5^{\circ}$. Task performance (percent success, total fuel used, and flight time required) and pilot ratings were obtained as a function of oscillation period when either the rate-command or direct mode was employed for spacecraft attitude control. The docking flights were initiated at a range of about 300 feet and were performed on a fixed-base docking simulator by pilots using only visual observation of the target for guidance information. In addition, a few results are included that show the effect of target oscillation amplitude and different path shapes traced by the target docking ring as a consequence of different yaw and pitch sine-wave combinations.

SYMBOLS

Measurements for this investigation were taken in the U.S. Customary System of Units. Equivalent values are indicated herein in the International System (SI) in the interest of promoting use of this system in future NASA reports.

The system of axes employed for the present study is shown in figure 1 and the symbols are defined as follows:

X,Y,Z — a rotating right-handed system of reference axes with origin located at center of gravity of Agena and with Z-axis directed along local vertical (see fig. 1)

X_b,Y_b,Z_b — right-handed system of body axes with origin located at Gemini center of gravity

X_t,Y_t,Z_t — right-handed system of body axes with origin located at Agena center of gravity

x,y,z — distances along X, Y, and Z reference axes, respectively, feet or meters

ψ,θ,ϕ Euler angles in specified order relating position of Gemini body axes and reference axes, degrees or radians (see fig. 1)

ψ_t,θ_t,ϕ_t instantaneous target Euler angles in specified order relating position of Agena body axes and reference axes, degrees or radians

$(\psi_t)_{max},(\theta_t)_{max},(\phi_t)_{max}$ maximum amplitudes of oscillatory motion, degrees or radians

p,q,r angular rates about Gemini body axes, degrees/sec or radians/sec

P period of target oscillation, seconds

ω rate of rotation of reference-axis system about earth at an altitude of 150 nautical miles, 0.0012 radian/second (1 international nautical mile = 6076.115486 international feet)

t time, sec

A dot over a quantity indicates the first derivative with respect to time.

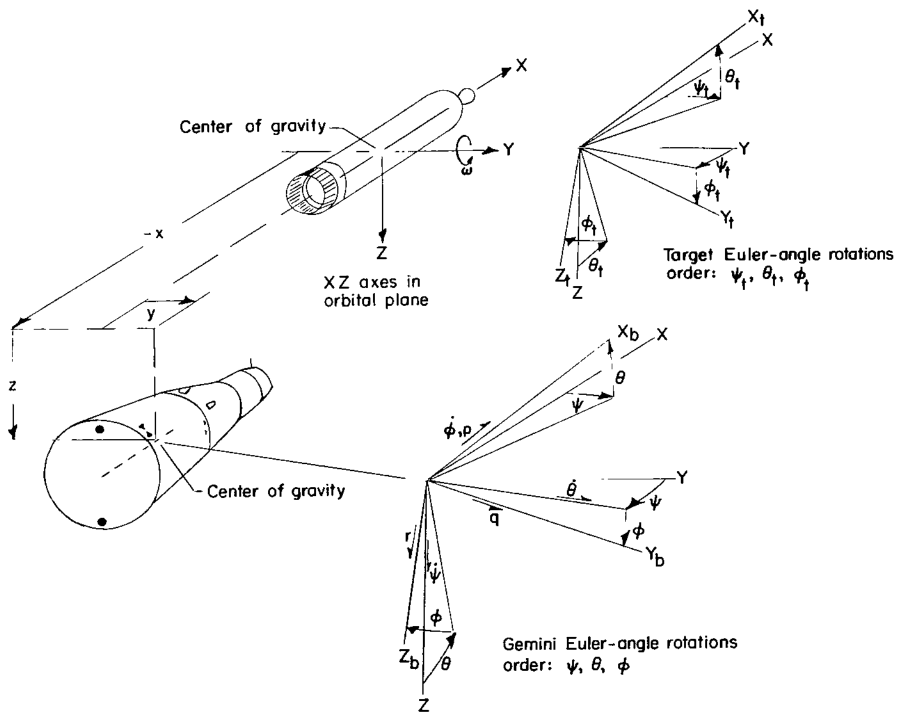


Figure 1.- System of axes used.

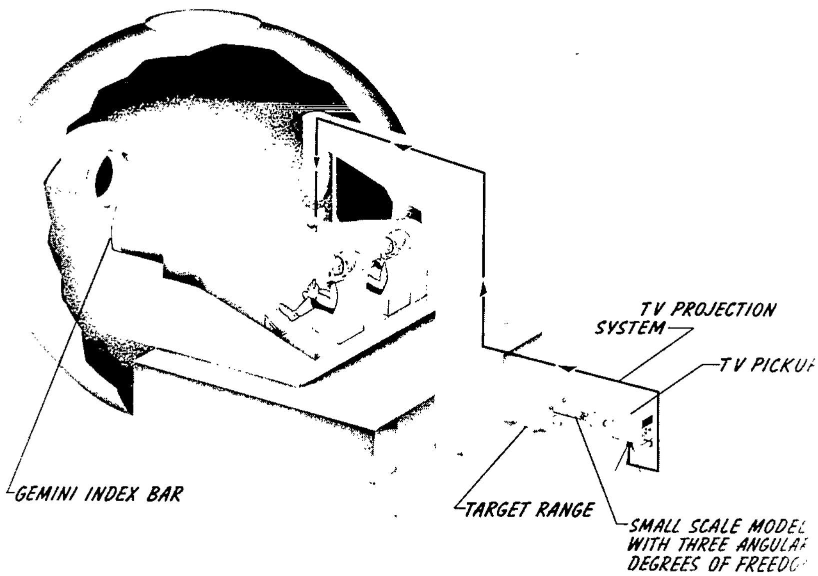


Figure 4.- Artist's isometric sketch of Langley fixed-base visual docking simulator.

the servo-driven mirror. An analog computer solved the equations of relative motion between the vehicles and provided the signals to drive the appropriate servomechanisms for the visual display.

Notable differences between the simulation and actual vehicles are:

(1) The pilot was seated vertically for comfort in a 1g field instead of inclined as in actual spacecraft.

(2) Model markings (fig. 5 and also ref. 5) employed to provide contrast in visual display are different from those of the Agena vehicle.

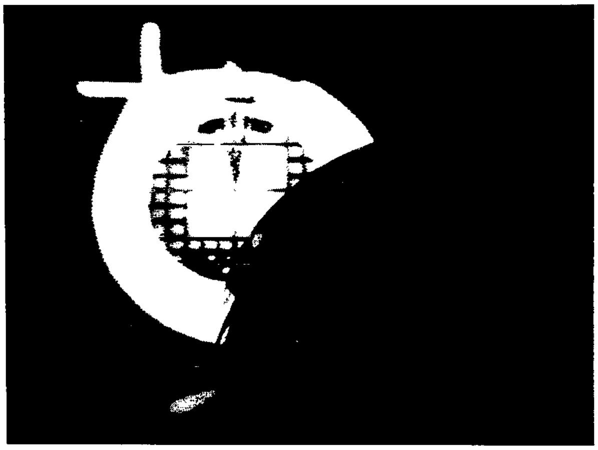
(3) Rear-mounted visual aids (details in ref. 5) providing additional boresight information and used for all flights herein are not employed on the actual target vehicle.

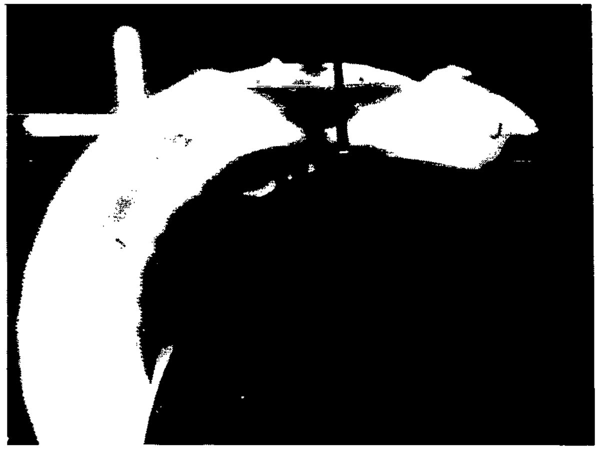
(4) The Gemini index bar, placed against the projection sphere to avoid parallax problems, was several feet further from the pilot's eyes than that in the actual spacecraft.

(5) Prototype Gemini hand controllers were not used.

Spacecraft Control Characteristics

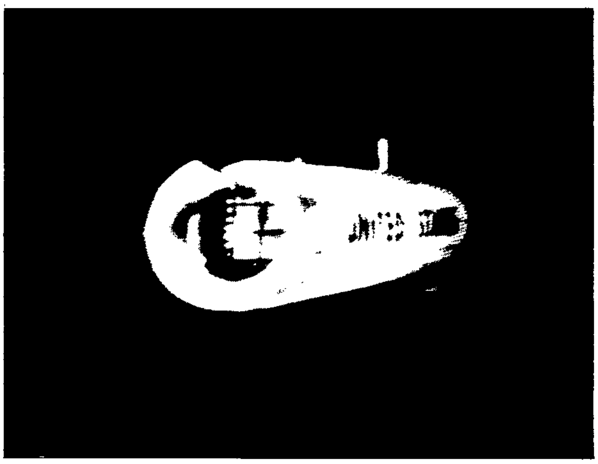
Realistic thrust levels for all control jets (obtained from actual static firings) were employed in the simulation. Time lags for these jets were not considered. Spacecraft control was commanded by the pilot by the three-axis fingertip controllers shown in figure 6 and in the sketch. Single-axis or multiple-axis inputs could be employed with either controller. A visual indication that the translation jets were firing was supplied

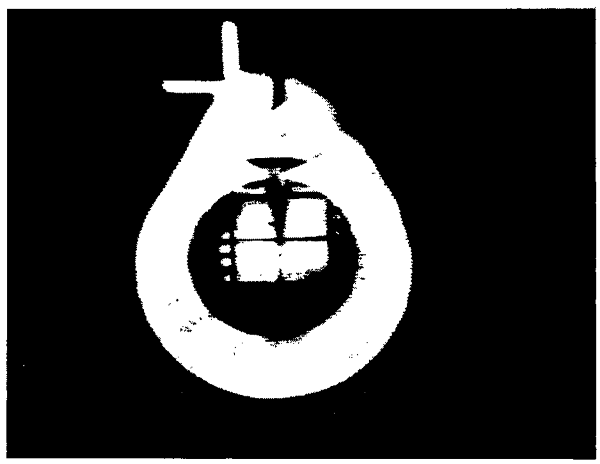




(a) A short longitudinal distance from contact with Gemini and Agena center lines alined and no angular misalinements.

(b) Ideal terminal conditions for docking run with Gemini and Agena center lines alined and no angular misalinements.

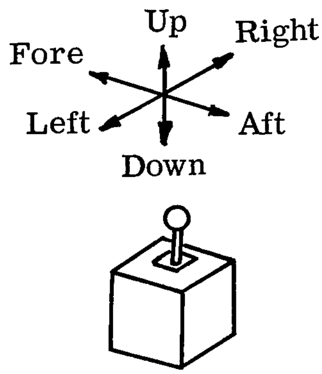




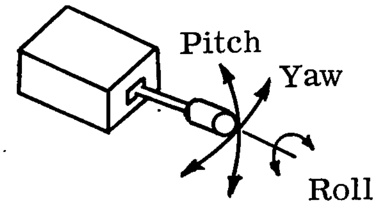
(c) Gemini displaced laterally.

(d) Gemini displaced vertically. L-64-8399

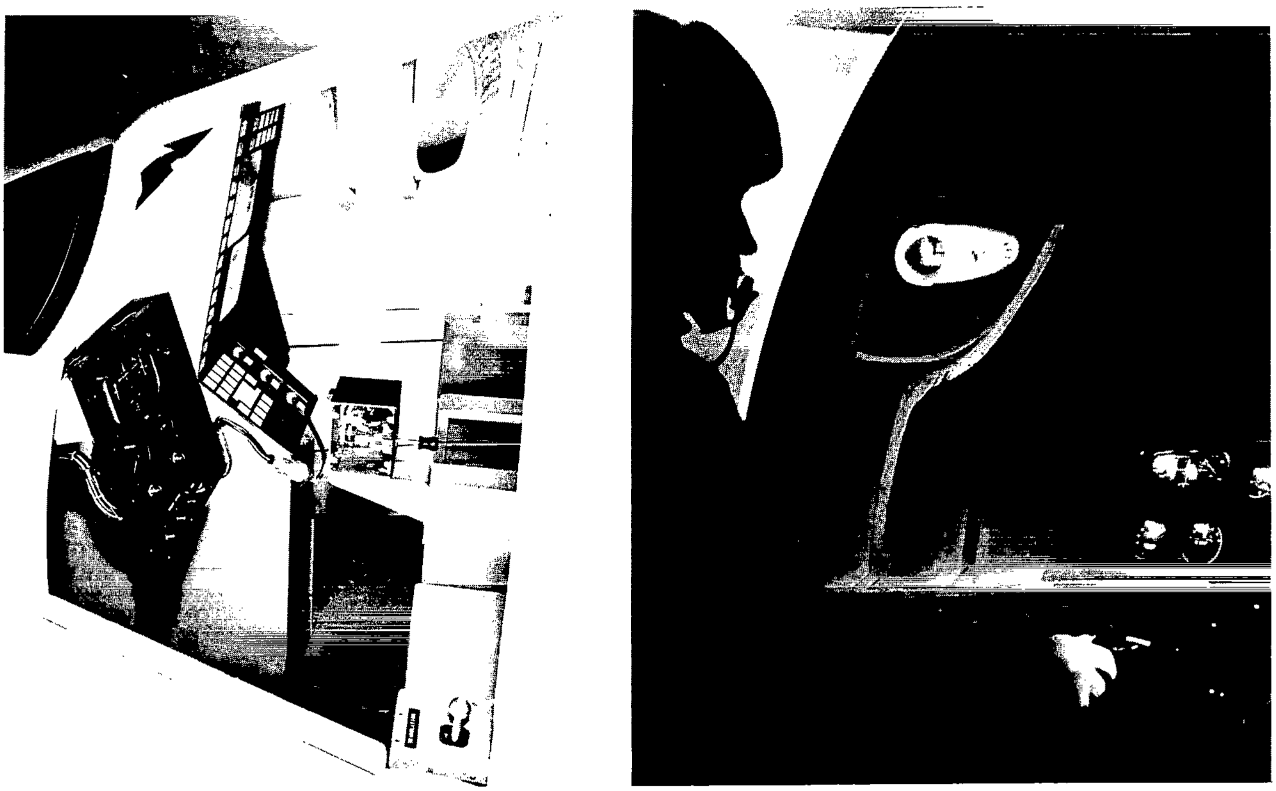
Figure 5.- Photographs of projected target image for fully illuminated lighting condition showing target markings employed in simulation. The vertical and horizontal bars mounted at rear of target are visual aids and were present for the data runs presented herein. The camera was located at the approximate eye position of the pilot.



Translation controller



Attitude controller



L-62-171
(a) Window panel removed showing the instrument panel and finger-tip controllers employed.

L-63-1649
(b) Internal view during flight showing target in view through spacecraft window.

Figure 6.- Photographs of Gemini mockup.

by means of three red indicator lights (one light for each axis) arranged horizontally on the left-hand side of the instrument panel. No visual indication of attitude jet firing was provided. For the rate-command mode of attitude control, a comparison of the values used in the simulation with those of the Gemini spacecraft is shown in the following table:

RATE-COMMAND ATTITUDE-CONTROL MODE

	Simulation	Spacecraft
Maximum roll rate	$\pm 8^\circ$/sec	$\pm 15^\circ$/sec
Maximum pitch rate	$\pm 4^\circ$/sec	$\pm 10^\circ$/sec
Maximum yaw rate	$\pm 4^\circ$/sec	$\pm 10^\circ$/sec
System deadband	$\pm 0.2^\circ$/sec	$\pm 0.2^\circ$/sec

It should be noted that the instruments shown on the panel in figure 6 were used only for simulator checkout and were covered during the test program.

Equations of Motion

Six-degree-of-freedom equations of motion were used in the simulation. The three moment equations were written with respect to a body system of axes with the origin at the center of gravity of the Gemini spacecraft. (See fig. 1.) The three force equations were written with respect to a rotating set of reference axes located in the Agena vehicle in circular orbit at an altitude of 150 nautical miles. The rotating axes were orientated such that the Z-axis was always directed toward the center of the earth and the X-axis was constrained to lie in the orbital plane. The Agena body axes and the reference axes were assumed to be coincident when the target was not oscillating. Target oscillations were obtained by driving the target Euler angles (ψ_t, θ_t, and ϕ_t) sinusoidally. The equations of motion used in the simulation are presented in reference 5.

Pilot's Task

The pilot occupied the left-hand seat (fig. 6), and his task was to take control of the Gemini from the initial conditions and to maneuver the vehicle until it began to enter the Agena docking ring within specified design tolerances. Only out-of-the-window observation of the target was used for guidance information. The pilot was permitted to use whatever technique he preferred to accomplish the task with no restraints on fuel and flight time. The specified design tolerances used herein were:

± 1 foot radial displacement between Gemini nose and docking ring centers

$\pm 10^\circ$ in relative attitude angles (yaw, pitch, and roll) of the two vehicles

1.5 ft/sec longitudinal contact velocity

0.5 ft/sec radial velocity between Gemini nose and docking ring

In this simulation, the pilots were allowed to maneuver only up to the flight termination point. The flights were terminated when the value of longitudinal displacement for properly alined vehicles placed the index bar of the spacecraft in the front plane of the docking ring. The run was considered to be out of tolerance if any one of the docking-ring design limitations was exceeded. Additional maneuvering to achieve in-tolerance linear and angular displacements at flight termination (as available in an actual space flight) was not permitted.

TEST CONDITIONS

Gemini Spacecraft

The parachute configuration of the Gemini spacecraft with a one-half fuel load was simulated. The initial conditions used for all the data flights presented herein were:

$$x = -250 \text{ ft}$$

$$y = 100 \text{ ft}$$

$$z = 75 \text{ ft}$$

$$\dot{x} = \dot{y} = \dot{z} = 0$$

$$\psi = \theta = \phi = 0$$

$$p = q = r = 0$$

Previous Gemini-Agena docking studies on this and other simulators have shown that other than the expected influence on fuel consumption and flight time, the effect of including reasonable linear and angular velocities and angular misalinements as initial conditions, and the use of different initial displacements were inconsequential to achievement of successful docking from this range. Only one set of initial conditions were used herein to permit fuel and flight-time comparisons.

Agena Target

Sinusoidal oscillations were initiated simultaneously in each of the target Euler angles at the beginning of each docking flight with an oscillating target. Conditions which resulted in three distinctly different types of motion of the docking ring relative to the reference axes were selected. These motions are referred to herein as straight-line, complex, and circular target motions. The expressions used and sketches of the resulting motions are presented as figure 7. Docking flights were made for a range of target oscillation periods from 180 to 30 seconds. Most of the flights were made for target maximum amplitudes of $\pm 5^{\circ}$. For a few flights, maximum amplitudes of $\pm 2.5^{\circ}$ and $\pm 10^{\circ}$ were used. The Agena target vehicle was fully illuminated for all flights.

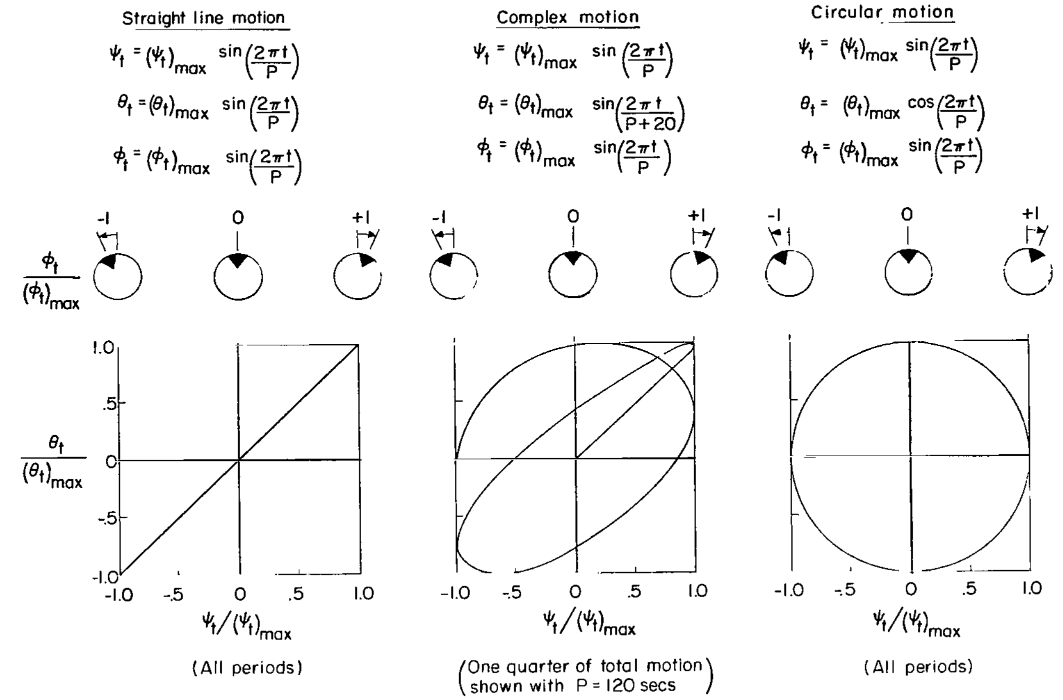


Figure 7.- Target equations and sketches of the three types of motion employed illustrating the trajectories of the target docking ring as viewed relative to the reference axis system. (For complex motion, path shape is function of period.)

RESULTS AND DISCUSSION

Piloting Technique

The basic technique of docking with an oscillating target was similar to that used with a rigidly stabilized target. For the initial conditions employed herein, closure was initiated by using either of the two methods of reference 5. Reasonable relative alinement was usually accomplished at distances of 50 to 100 feet from the target. During these initial maneuvers, target oscillations were ignored.

Within the final 50 feet of the approach, the technique for a rigidly stabilized target was (1) to reduce the closure rate to a value of about 1/2 ft/sec and leave it uncorrected to flight termination unless out-of-tolerance conditions existed and (2) to reduce the translational and angular misalinements as the range decreased. (The presence of a parallax angle complicated the latter task. See fig. 5.) With the target oscillating the same technique was applied successfully when the period of oscillation was large. For the shorter periods, the attempts to reduce misalinements with decreasing range degraded to simple maintenance of in-tolerance conditions. The usual approach resulted in out-of-tolerance conditions just prior to docking. The pilots consequently stopped the closure rate with the vehicles positioned a short distance apart and applied transverse translation and attitude corrections to achieve in-tolerance conditions. (Yaw and pitch misalinements were of comparable difficulty to correct, but that for roll was simpler to correct.) Once in-tolerance conditions were attained, the closure rate was reinitiated. For the very short periods (under 60 seconds), the magnitude of the closure velocity was increased with decreasing period.

During the final approach, the pilots ignored the star field when displayed and concentrated exclusively on the target. Since only relative motion can be detected from observation of the Agena, target oscillations, as such, are not evident to the pilot. The fact that control inputs were applied to null transverse displacements and angular misalinements in the manner of a rigidly stabilized target is evident in the oscillatory nature of the trajectory traces shown in figure 8. For this part of the flight the visual aids employed on the target (fig. 5) were helpful in detecting changes in target aspect.

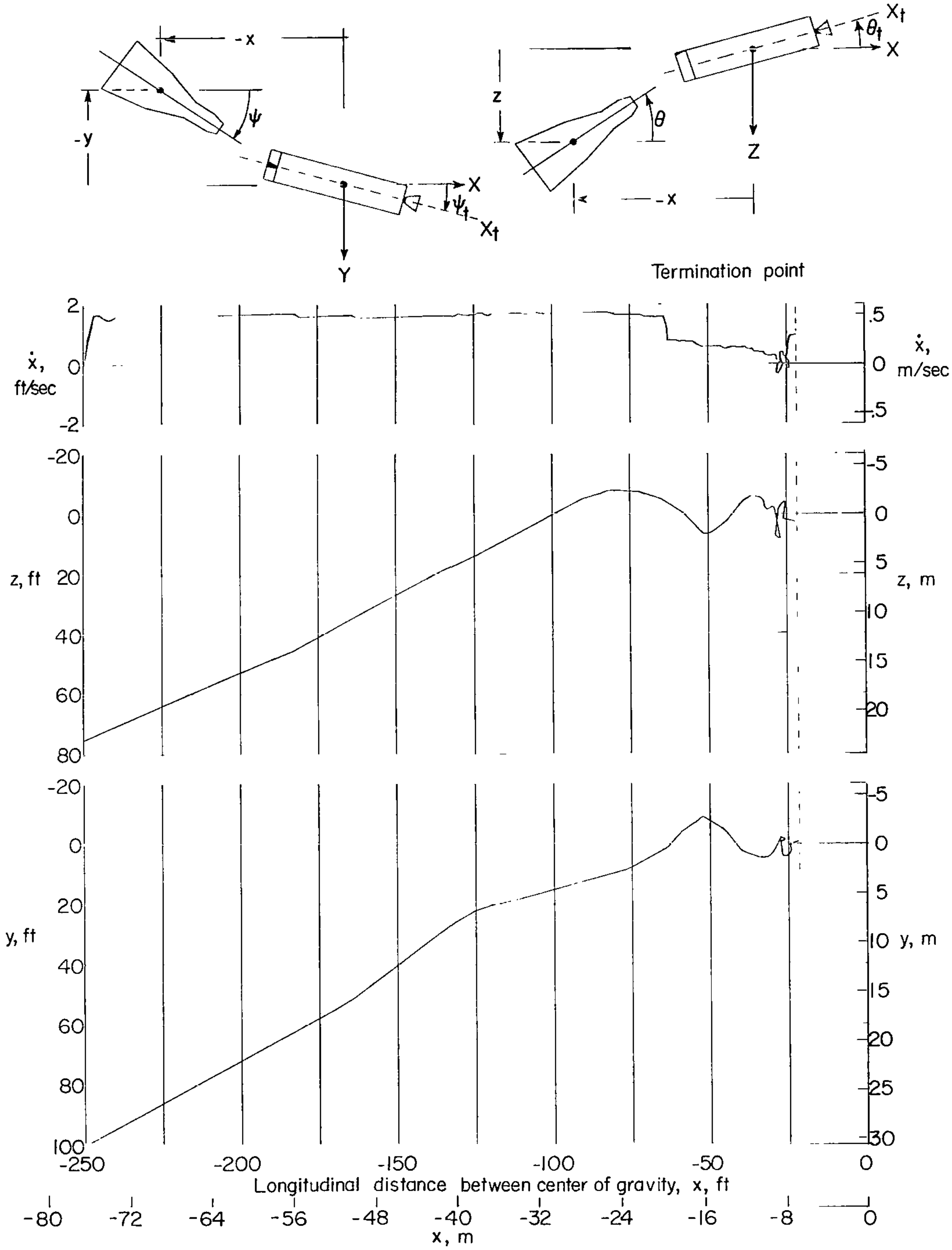
Pilot Ratings and Task Performance

Pilot ratings were obtained for various oscillatory test conditions with the Cooper rating schedule (ref. 6) shown in the following table:

Adjective rating	Numerical rating	Description	Primary mission accomplished
Satisfactory	1	Excellent, includes optimum	Yes
	2	Good, pleasant to fly	Yes
	3	Satisfactory, but with some mildly unpleasant characteristics	Yes
Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes
	5	Unacceptable for normal operation	Doubtful
	6	Acceptable for emergency condition only	Doubtful
Unacceptable	7	Unacceptable even for emergency condition	No
	8	Unacceptable – dangerous	No
	9	Unacceptable – uncontrollable	No
Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No

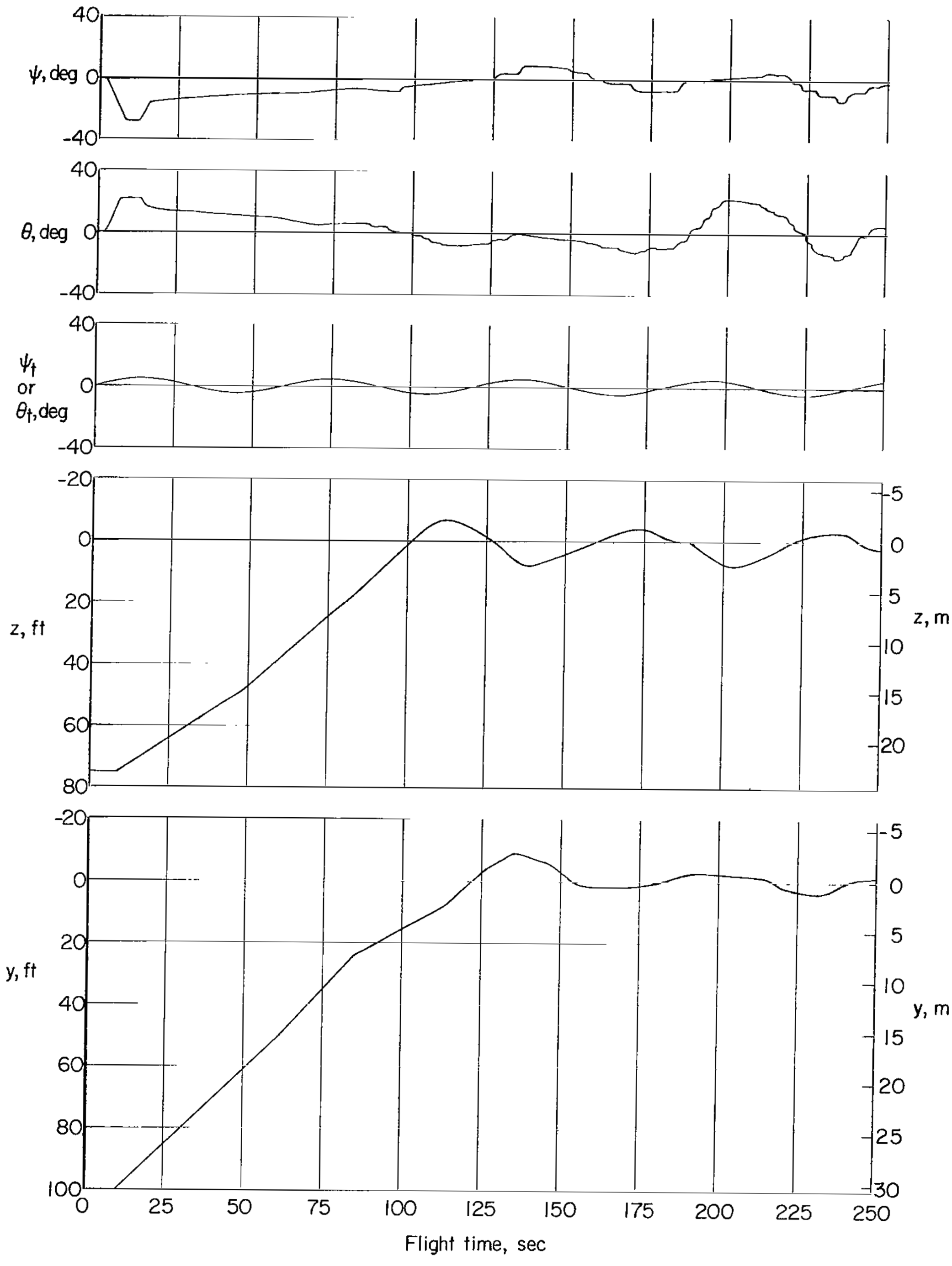
Ratings and task performance results (percent success, fuel used, and flight times required) are presented in the following order:

	Figure
Rate-command mode, $\pm 5^{\circ}$ amplitude results	9
Direct mode, $\pm 5^{\circ}$ amplitude results	10
Comparison of results for the two modes	11
Effect of oscillation amplitude (rate-command mode)	12
Effect of circular motion of docking ring (rate-command mode)	13



(a) Closing velocity and trajectory traces.

Figure 8.- Trajectory, closing velocity, and time-history traces for a docking flight with the target oscillating at ±5° amplitude at 60-second period made by research pilot A using the rate-command attitude-control mode. (Results are representative of docking flights made by all subjects at the shorter oscillation periods.)



(b) Time-history traces.

Figure 8.- Concluded.

The data were obtained by the subjects (two NASA research pilots and two engineers) in groups of flights taken at various occasions over a time interval of several months. For most of the groups, several docking flights with the target not oscillating ($P = \infty$) were obtained. These values were used to normalize the remaining oscillatory data for each group to account for some difference in the fuel and flight time levels for the same test conditions obtained by the same pilot but taken at different times and for the differences in the results of the four subjects. Because of the scatter of the individual data points, data boundaries are also shown in the figures. Most of the data were obtained for an oscillation amplitude of $\pm 5^{\circ}$ and with the docking ring tracing out a straight-line path in the reference-axis frame (fig. 7). Fuel and flight-time comparisons between these results and those when the docking ring was performing a complex trace indicated no difference and, consequently, the results were combined. When the circular trace was employed, some difference was noted at the lower periods and these data are shown separately.

The rate-command data (fig. 9) and the direct-mode data (fig. 10) show the same effect of oscillation period. The percentage of successful completions decreased (to as

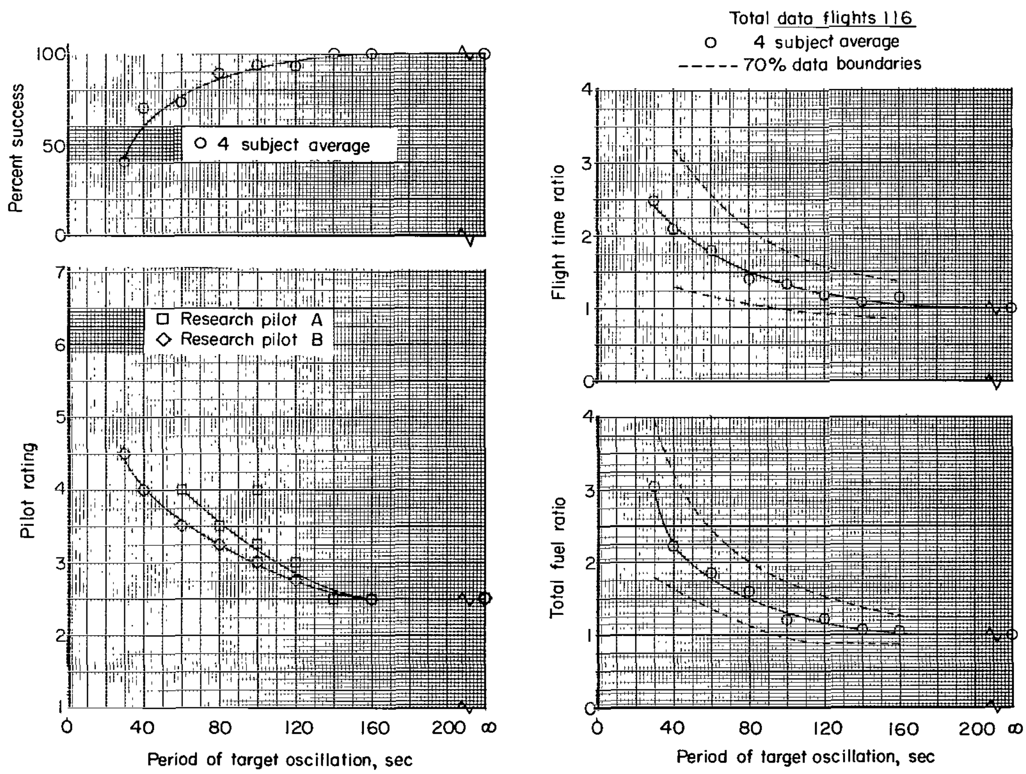


Figure 9.- Docking performance results obtained using the rate-command attitude-control mode by 4 subjects (2 NASA research pilots and 2 engineers) and corresponding research pilot ratings as a function of period for the Agena target vehicle oscillating sinusoidally with a maximum amplitude of $\pm 5^{\circ}$. (Nonoscillating target values: average fuel, 11.6 lb; average flight time, 2.8 min.)

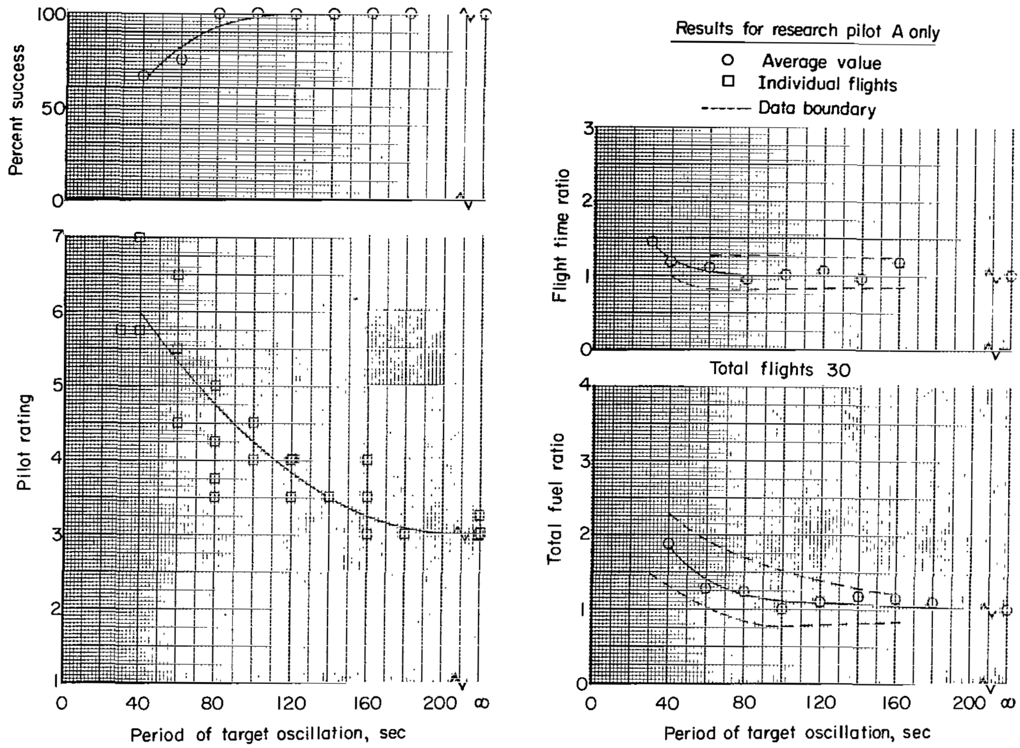


Figure 10.- Docking performance results and pilot ratings as a function of period for flights using the direct mode of attitude control (acceleration command) with the Agena target vehicle oscillating sinusoidally with a maximum amplitude of $\pm 5^{0}$. (Nonoscillating target values: average fuel, 7.0 lb; average flight time, 3.9 min.)

low as 40 percent at $P = 30$) as the oscillation period decreased. The increased complexity of the docking task with decreasing period is reflected in the corresponding less favorable pilot ratings. Associated increases in fuel and flight time occurred with decreasing period. As might be expected, the docking-ring velocity tolerances were exceeded in most of the out-of-tolerance flights at the lower values of period. For an oscillation period greater than 160 seconds, task performance and pilot ratings comparable with those for a rigidly stabilized target were obtained.

All performance results for the docking flights using the direct-control mode were obtained by research pilot A who was highly skilled in handling the Gemini dynamics since he had accumulated over 600 docking flights in the fixed-based simulator used for these tests and the moving-base simulator of reference 3. The docking task using the direct-control mode is difficult to learn because of the presence of control coupling even with the target not oscillating as indicated in references 2 and 5. Including target oscillations increases the difficulty of the task and achieving the fuel and flight time levels presented herein requires a highly trained pilot.

The data comparison for the two attitude-control modes (fig. 11) shows the pilot rating curves to be almost parallel, and indicates that the increased task difficulty with

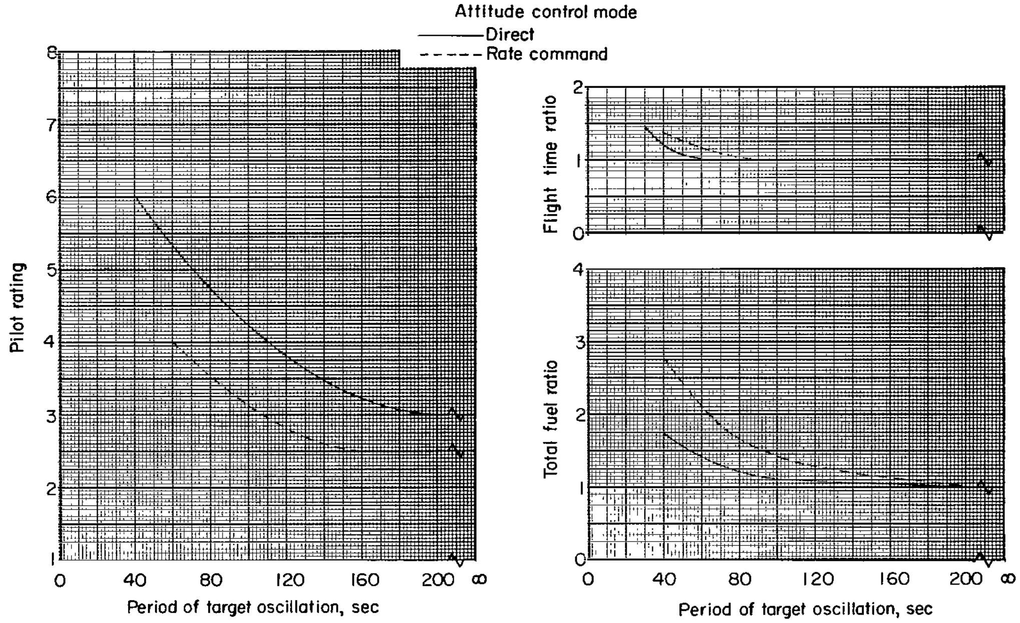


Figure 11.- Comparison of the performance results of research pilot A and pilot rating for the two modes of attitude control. Oscillation amplitude, $\pm 5^{\circ}$.

decreasing period is not influenced by the mode of control. It is of interest to note the higher fuel consumption of the rate-command mode at the lower values of period. A possible contributing factor is believed to be the low maximum angular rates of the rate-command mode available in the simulation which manifests itself in additional delay near the termination point and requires more control inputs in order to complete the docking.

A few docking flights (all 2.5° and 10.0° flights represent single runs at a given period) were made by research pilot B using the rate-command mode to illustrate the effect of oscillation amplitude (fig. 12). It should be noted that at $\pm 5^{\circ}$ amplitude, the target motions result in maximum linear displacements of the docking ring approaching the design tolerance of ± 1 foot and angular misalinements of one-half the design tolerance. When target amplitudes in terms of docking-ring design tolerances are considered, it would be expected and the results show that oscillation amplitudes of $\pm 2.5^{\circ}$ have little influence on the docking task except possibly at very small values of period where the docking-ring velocity tolerances could easily be exceeded. (The fuel and flight-time variations shown for the period range between 40 and 20 seconds are within the range of scatter for such data.) Above about $\pm 2.5^{\circ}$ amplitude, increasing amplitude for a given value of period would be expected to increase the task difficulty and would result in increases in

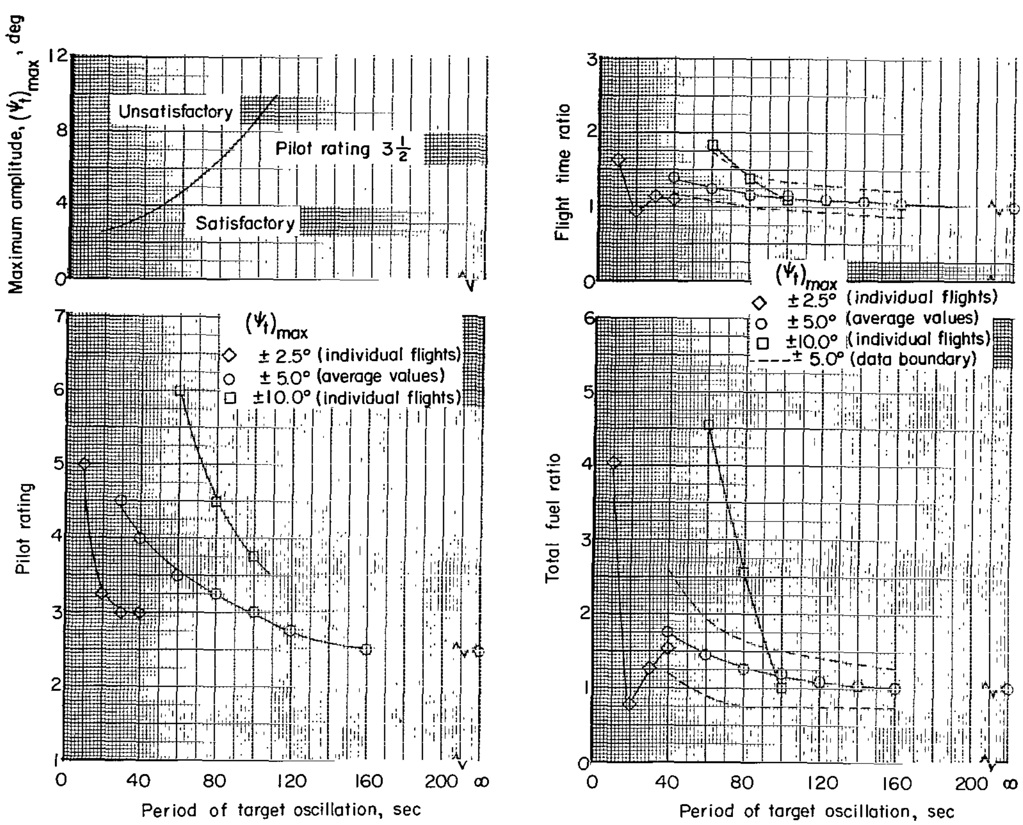


Figure 12.- Effect of oscillation amplitude on the docking results of pilot B using the rate-command attitude-control mode.

fuel used, increases in flight time required, and less favorable pilot ratings. The few data points presented on figure 12 indicate that for amplitudes of $\pm 10^{0}$ or less, large effects of oscillation amplitude appear to occur in the period range below about 120 seconds. A tentative amplitude-period boundary for a given level of task difficulty (given pilot rating) is also presented.

Fuel and flight-time results from tests in which the docking ring performed a circular trajectory trace about the longitudinal reference axis (fig. 7) are presented and compared in figure 13 with the combined result of tests with the docking ring performing straight-line and complex trajectory traces of the same motion amplitude. The docking task was felt to be somewhat harder at the lower values of period for circular motion than for the other two docking-ring traces. The limited fuel results show an increase at the low values of oscillation period. For most of the range of oscillatory periods considered, comparable results were obtained for the three trajectory paths.

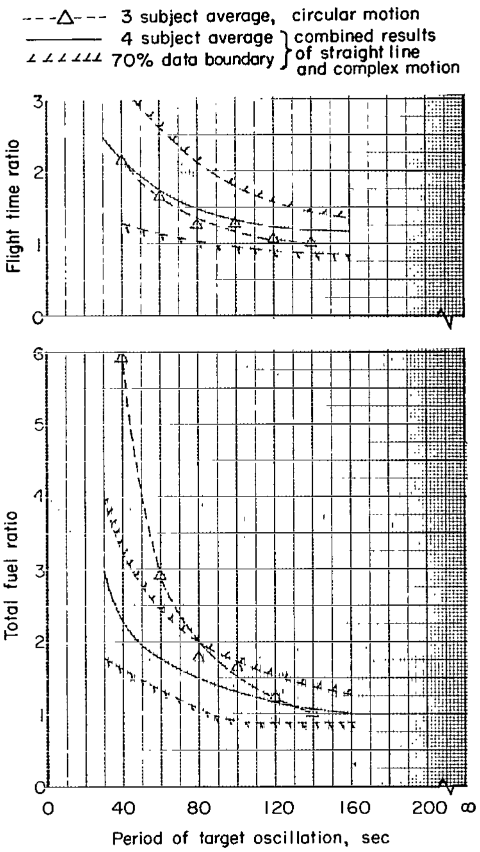


Figure 13.- Effect of path shape as traced by target docking ring on fuel and flight-time results obtained from docking flights made by using the rate-command attitude-control mode for the target oscillating at ±5° amplitude.

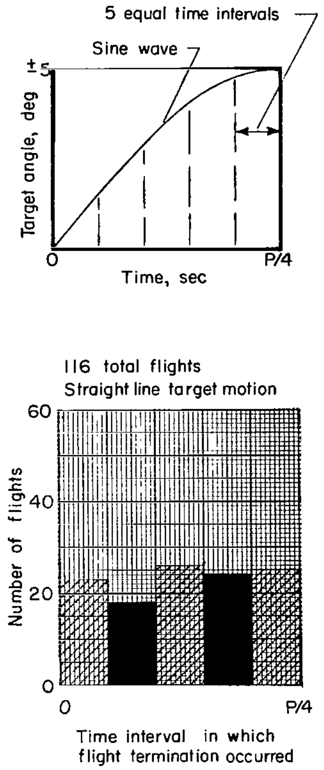


Figure 14.- Variation of number of flights with time during the target cycle that flight termination occurred. Note that each quarter cycle of target motion is represented by the 5 equal time intervals. Rate-command and direct-mode results combined; ±5° amplitude data.

End Conditions

The percent success ratio previously used summarizes the results of most of the terminal conditions of the docking flights. The position of the target in its cycle at flight termination is of particular interest, however, to ascertain whether the use of sinusoidal waveforms in the angles influences the docking results. A distribution curve for terminal values of target angle is presented in figure 14 for those flights with the target docking ring performing a straight-line trajectory trace. Since roll, pitch, and yaw motions are in phase for this trace, any influence of the sinusoidal variation should be apparent. Only the $\pm 5^{\circ}$ amplitude results were used for figure 14. In addition, the rate-command and direct-mode data were combined to provide a larger data sample. The distribution shown resulted from a combination of data for all periods since it was found that the period of oscillation did not affect the distribution. Also, comparable results were obtained from a similar analysis of the complex trajectory data.

If the sinusoidal waveform used for the target limit cycle has no influence on docking, completion of the docking task should occur equally well at any time during the target cycle. The distribution (fig. 14) was obtained simply by determining the number of flights terminating within each of the angular limits (irrespective of sign) associated with five equal time increments as depicted in the figure. The constancy of the distribution with time indicates that the pilots were not cognizant of the position of the target in its cycle during the terminal maneuver. As a consequence, the constancy of the distribution and lack of a period effect indicate that the use of sinusoidal waveforms do not appear to influence the piloting task or docking results. Comparable results would be expected if a simple reaction-jet system for target stabilization had been employed. Sinusoidal variations can influence docking results to some extent; however, such influence for the three-degree-of-freedom target oscillations of arbitrary phasing appears to be for the range of periods below 30 to 40 seconds as in the single-degree-of-freedom tests of reference 5.

CONCLUSIONS

A brief study was made with a fixed-base simulator employing closed-circuit television to determine the effects of target sinusoidal oscillations in three angular degrees of freedom on pilot-controlled Gemini-Agena docking. Flights were initiated at a range of about 300 feet and were performed by using both the rate-command and direct (acceleration command) attitude-control modes with only visual observation of the target for guidance. Vehicle mass and moments of inertia simulated the parachute configuration of the Gemini spacecraft with a one-half fuel load. The results of the study apply to a fully illuminated target with rear-mounted visual-aid bars for additional boresight information and are as follows:

1. For docking flights using either the rate-command or direct attitude-control modes, task performance and pilot ratings comparable with those for a rigidly stabilized target were obtained with the target oscillating at $\pm 5^{\circ}$ amplitude in each of three angular degrees of freedom at oscillation periods of 160 seconds or greater. Fuel consumption and flight time increased, pilot ratings were less favorable, and the percentage of successful dockings decreased as the period of the oscillations was reduced below 160 seconds.

2. For the rate-command attitude control mode, limited results on the effect of oscillation amplitude indicate that for an amplitude of 2.5°, target oscillations have little influence on the docking task except at small values of period (30 to 40 seconds or less) where docking-ring velocity tolerances can more easily be exceeded. For the amplitude range between $\pm 2.5^{\circ}$ and $\pm 10^{\circ}$, increasing the motion amplitude for a given value of period (below about 120 seconds) results in increases in fuel used, increases in flight time required, and less favorable pilot ratings.

3. Of the three paths traced by the target docking ring in the reference-axis frame (straight line, complex, and circular), the circular trajectory was found to provide a somewhat more difficult condition for docking at the shorter periods investigated. For most of the range of oscillatory periods considered, comparable results were obtained for the three trajectory paths.

4. During the terminal maneuver the pilots were not cognizant of the position of the target in its cycle. It appears that the use of sinusoidal waveforms to represent target stabilization motions was of little consequence to the docking task for the range of periods of the tests.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., January 14, 1966.

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